UXO DETECTION USING ULTRA-WIDEBAND SYNTHETIC APERTURE RADAR

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ABSTRACT

The U.S. Army Research Laboratory (ARL), under the sponsorship of the Strategic Environmental Research and Development Program (SERDP), is conducting experiments to establish and enhance the ability of low-frequency, ultra-wideband (UWB) synthetic aperture radar (SAR) to detect and discriminate unexploded ordnance (UXO). Preliminary investigations using ARL's BoomSAR—a UWB (50–1200 MHz) radar mounted atop a mobile boom lift platform—concluded that the radar image texture and frequency-dependent scattering from mines and mine-like targets could be exploited in the development of automatic target detection algorithms.

To support further investigations, ARL established extensive UXO test sites at the U.S. Army Yuma Proving Ground, Arizona, and Eglin AFB, Florida. The soils at both test sites have been characterized in terms of physical, chemical, and electromagnetic properties. For each of the approximately 500 inert ordnance test targets at each site, precise location, depth, and orientation information was recorded. This information helps researchers to better understand the phenomenology associated with UXO target scattering and to more accurately evaluate and modify data processing programs. The ultimate goal is to develop innovative automatic target detection algorithms that provide a high probability of detection with an acceptable false-alarm rate under varying environmental conditions and operational scenarios.

BOOMSAR SYSTEM

The U.S. Army Research Laboratory (ARL) designed and fabricated an ultra-wideband (UWB) synthetic aperture radar (SAR) measurement asset to collect data to support the validation of high-fidelity electromagnetic models and the development of unique low-frequency target detection algorithms. In its present configuration, the radar collects side-looking SAR data from atop a 45-m telescoping mobile boom lift; hence, the system is called a "BoomSAR" (see figure 1).

Figure 1. BoomSAR system.

The BoomSAR system is capable of collecting repeatable data that may be used to define the upper bound of performance for UWB radar of this type and support tradeoff analyses associated with determining frequency bands, integration angles (resolution), power levels, polarizations, and motion compensation requirements of advanced development systems.

The radar spans a frequency range (50–1200 MHz) extending beyond the frequency bandwidth of potential future operational ground-penetrating systems [1]. Post-processing of the wideband data allows for the evaluation of numerous subbands to determine the optimal frequency range for detecting the desired concealed target in postulated radar designs. Because it emulates the trajectory that would be flown by airborne radar systems, the BoomSAR can provide insight into the potential of an airborne UWB SAR.

In a four-antenna configuration (two transmit and two receive antennas), the radar proceeds along the aperture while alternately firing its two impulse transmitters (alternately generating horizontally and vertically polarized waves) and simultaneously receiving all return signals on both the horizontal and vertical receive antennas. These antennas feed high-speed analog-to-digital converters (ADC) that act as base-band receivers. In each channel, high-speed array processors operate on the ADC data to perform data interleaving, integration, filtering, and resampling to produce 8 gigasample/s equivalent data records. Interleaved output along with the associated position data from a robotic theodolite is typically sent to six 1.3-GB magneto-optic CD drives, three for each (horizontal and vertical) channel.

In operation, the 30-ton BoomSAR system is driven at approximately 1 km/hr, while the radar illuminates a 300-m swath (in range) that starts approximately 50 m from the boom lift and extends out to about 350 m (see figure 2). Boom height and antenna depression angle may be varied to provide different “looks” at the target area. Further, it provides a high degree of control in the design and execution of test scenarios.

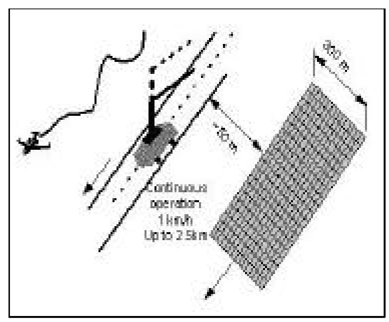


Figure 2. Mode of operation.

UNEXPLODED ORDNANCE (UXO) TEST SITES

ARL has established extensive UXO test sites at the U.S. Army Yuma Proving Ground (YPG), Arizona, and Eglin AFB, Florida, to support UWB SAR data collections. Broad data sets collected at these sites will support phenomenological investigations into electromagnetic propagation through varying dielectric media and the development of advanced techniques and algorithms for detecting UXO. Test site attributes described in the following sections include topography, targets, layout, ground truth, and soils.

Topography

Yuma Proving Ground is located in southwestern Arizona, approximately 30 miles north of Yuma, AZ. The UXO test area at YPG is located within the ARL Steel Crater Test Site at Phillips Drop Zone. The soil at Phillips Drop Zone—training site of the Army’s Golden Knights precision parachute team—is turned over to a depth of about 2 ft and normally free of vegetation, an almost homogeneous soil layer. This feature permits the investigation of electromagnetic wave propagation studies in a realistic but relatively easily definable soil. Surrounding the Drop Zone are naturally occurring clutter areas. An aerial view of the entire Steel Crater Test Site is shown in figure 3.

Eglin AFB is located in the Florida panhandle, due north of Fort Walton Beach, FL. The UXO test area at Eglin is located at Test Area (TA) C-62, an active range comprising 1290 acres situated approximately 20 miles northeast of Eglin's Main Base. The BoomSAR will be operated on a stabilized clay 5000 ft by 70 ft landing strip that runs adjacent to the western edge of TA C-62. The UXO test area is approximately 700 m by 100 m and is situated about 50 m west of the landing strip. The terrain of TA C-62 is mainly flat, and the vegetation consists of open stands of turkey, post, and live oak with scattered sand and longleaf pine. The area is cleared yearly to control the rampant growth of runner oak, yucca, wiregrass, indiangrass, paspalum, and dropseed, with numerous annual forbs. An infrared (IR) image of TA C-62 is shown in figure 4.

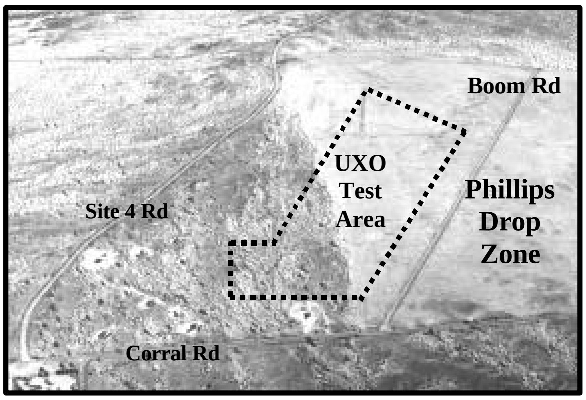


Figure 3. Aerial view of Steel Crater Test Site at YPG.

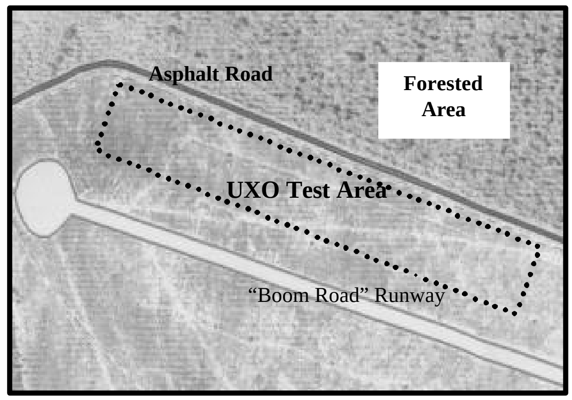


Figure 4. IR image of TA C-62 at Eglin AFB.

Soils

The University of Florida performed in-situ soil characterizations at YPG [2–6] and Eglin AFB [7] in September 1997 and August 1998, respectively. Laboratory soil tests and analyses were also performed. The objectives of this effort were to characterize the soil in terms of physical, chemical, and electromagnetic properties. Properties of particular interest for ground-penetrating radar performance estimates are the soil dielectric permittivity, soil conductivity, and soil moisture. These and other important properties have been measured for soils at both test areas.

Time-domain reflectometer (TDR) tests were made with probes inserted directly into the ground, soil visual inspections and tests were made in the field, and soil samples were collected for further laboratory testing at the University of Florida. The TDR makes a measurement of a pulse waveform input to parallel probes inserted into the soil. From the TDR measurements, the effective velocity of the pulse in the soil is measured and, in turn, the soil dielectric constant (approximately the real dielectric permittivity) and volumetric moisture content can be calculated. The characteristics of the TDR pulse return also allow estimates of low-frequency soil conductivity. Soil samples were collected to make bulk density measurements, gravimetric moisture measurements, soil composition, dc conductivity, and other measurements in the laboratory.

Previous work with YPG soils and results of soil modeling efforts are used here to estimate the complex dielectric permittivity of several Yuma soils with different compositions and at different moisture contents; the most recent work was by Miller and Kurtz. Prior modeling work has shown that the soil composition (sand and clay) can be used in a model to make reasonable estimates of dielectric permittivity after modifying the model to "fit" measured permittivity data for Yuma soils. Such a modified model has been used here to make dielectric permittivity estimates for several Yuma soils with varying moisture content. The soil dielectric permittivity from the model is then used to make soil attenuation versus frequency estimates. Estimated values for the attenuation (dB/m) as a function of frequency and soil moisture at one particular area (soil area YA2) of YPG are shown in table 1. The soil at this location is composed primarily of sand (86.20%) and clay (5.40%).

Although Eglin soils have not been modeled, the University of Florida expects that signal loss due to the soil will be approximately fifty percent lower than the attenuation experienced at Yuma, due mainly to the lower conductivity at the Eglin AFB.

Table 1. Model predictions of attenuation (dB/m) as a function of frequency and soil moisture (% water by weight) at YPG soil area YA2.

	Frequency (MHz)						
	74.47	149.76	301.83	501.35	696.36	899.20	1099.60
Soil Moisture	**Attenuation (dB/m)**						
1%	4.64	5.08	7.08	10.01	12.69	15.15	17.82
2%	5.48	6.03	8.48	12.17	15.65	18.95	22.61
3%	5.94	6.55	9.30	13.53	17.64	21.62	26.14
4%	6.21	6.88	9.85	14.52	19.16	23.77	29.06
5%	6.38	7.10	10.24	15.29	20.42	25.59	31.62
6%	6.49	7.24	10.53	15.92	21.49	27.19	33.92
7%	6.55	7.33	10.75	16.45	22.44	28.64	36.03
8%	6.59	7.39	10.92	16.91	23.28	29.97	37.99
9%	6.60	7.43	11.06	17.31	24.06	31.20	39.83
10%	6.59	7.44	11.16	17.67	24.77	32.36	41.57

The photographs in figure 5 illustrate different levels of soil moisture and vegetation growth at Phillips Drop Zone at YPG. From left to right, these photos were taken in (1) January 1996, when vegetation was sparse and the soil moisture content was approximately 1 percent; (2) January 1998, when the YPG desert was in bloom, and the soil moisture content was at nine percent as a result of Tropical Storm Nora and the El Niño rainy season; and (3) June 1998, when the vegetation was dry and brittle, and the soil moisture content was approximately five percent.

Figure 5. Photos of Phillips Drop Zone taken in January 1996, January 1998, and June 1998.

Targets

Target types were selected based primarily on UXO detection requirements within the Department of Defense (see figure 6). Only inert targets were placed in the test areas. Targets were buried at specific depths and orientations to (1) present realistic scenarios (i.e., depth and orientation of UXO at DoD test and training ranges) and (2) provide researchers a wide variation of known aspect angles, thereby fostering the implementation and evaluation of new and advanced data processing algorithms. Table 2 gives an itemization of the targets placed at YPG and Eglin AFB, arranged according to type and depth.

Table 2. Type, quantity, and depth (surface to tail) of test targets placed at YPG, and Eglin AFB.

	TARGET DEPTH (surface to tail)											
	Surface or flush		Subsurface to 0.5 ft		Subsurface 0.5 –1 ft		Subsurface 1–2 ft		Subsurface 2 –3 ft		Subsurface 3–6 ft	
TARGET TYPE	YPG qty	Eglin qty	YPG qty	Eglin qty	YPG qty	Eglin qty	YPG qty	Eglin qty	YPG qty	Eglin qty	YPG qty	Eglin qty
Artillery Shells												
105 mm	28	8	12	10		16	12	8				
155 mm	28	11	8			11		21	12	8		
Rockets												
2.75 in.		4		8		8		4				
2.75 in. w/ HE Case	24	4	12			16		4	12			
Mortar Shells												
60 mm	20	8	8	24	12	8						
81 mm w/ tail	28	1	4	4	8			4				
81 mm w/o tail		8		4		18		4				
Submunitions												
M-42	16		32									
BLU-63	22		10									
M-68	22		10									
BLU-97	32	8	16	28								
M-118	32	14	16	24								
BDU-28		16		20								
Bombs												
BDU-33 w/ tail		4		8		4		4				
BDU-33 w/o tail		8		8		8		4				
250–2000 lb.	1	2			3		8	2	9		8	4
Mines												
Gator	16	8	8	35								
VS1.6	12	4	8	12								
M12	16	0	4									
M20		4		8								
Volcano		4		12								
TTCP Simulant		4		4								
Plastic Simulants		6		12								
PMN	8											
POM-Z	4											
TOTAL	309	126	148	221	23	89	20	55	33	8	8	4

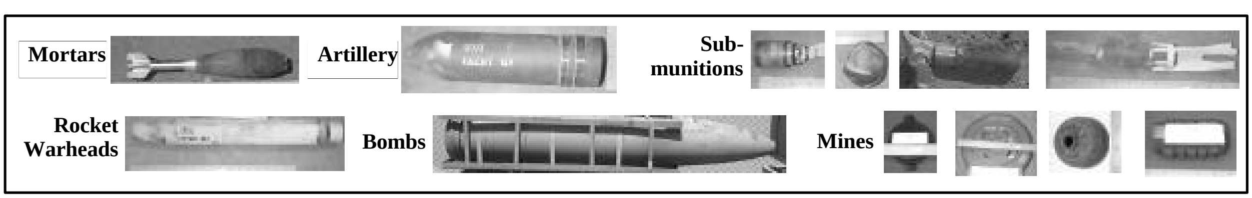


Figure 6. Photos of some of the targets placed in UXO test areas at YPG and Eglin AFB.

Layout

The test targets at both sites, excluding the bombs at YPG, were positioned in parallel rows according to target type. A summary of the layout features of both test sites is given in table 3.

Table 3. Salient features of test site layouts.

Feature	*UXO Test Area at Yuma Proving Ground*	*UXO Test Area at Eglin AFB*
Approximate Size	27 acres	20 acres
Number of Rows	39	85
Distance Between Rows	7 m (rows 1–27) 10 m (rows 28–39)	7 m (rows 1–50) 10 m (rows 51–85)
Distance Between Targets (min)	7 m	7 m
Row Length	112 m	70–100 m
Targets Per Row (max)	16	10–14
Total Targets Placed	541	503

At YPG, 18 bombs are in the natural occurring clutter area near Corral Road and 11 are in the Phillips Drop Zone. In addition, six holes were dug and immediately back-filled in the naturally occurring clutter area to investigate the radar signatures of disturbed soil versus actual targets. Figure 6 shows the entire test area, which includes the UXO as well as the vehicles, mines, boxes, disks/back-filled holes, repeaters, barrels and clones at the original Steel Crater Test Site.

At Eglin AFB, the first location in each row, located approximately 50 m from the runway (Boom Rd), has been reserved for the future placement of 1-ft-long pieces of rebar to serve as registration targets. Surface items will be placed just prior to the data collection, and additional items will be added at a predetermined interval during the data collection to support the evaluation of change detection algorithms. Figure 7 shows the layout of TA C-62. Prior to placement of the test targets at TA C-62, pre-existing UXO (mostly BDU-33 training bombs) were removed from a 2-m-radius area surrounding test target locations.

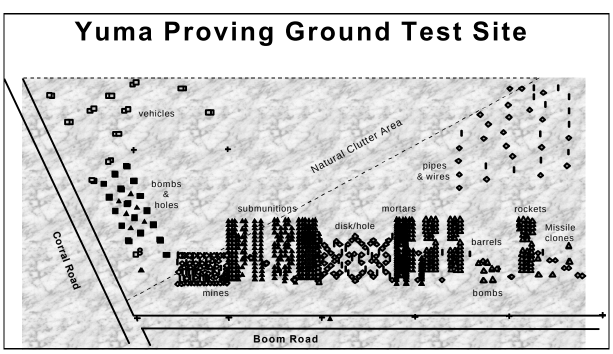


Figure 7. Layout of test area at YPG.

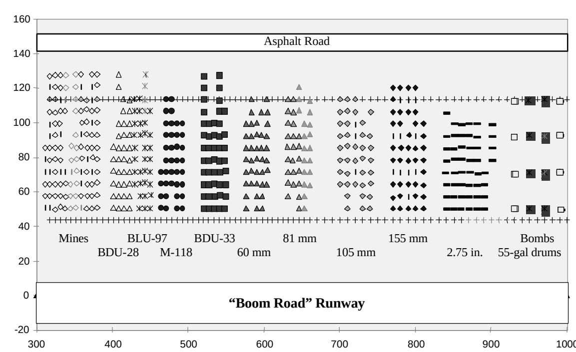


Figure 8. Layout of test area at Eglin AFB.

Ground Truth

To afford researchers a better understanding of sensor data, detailed ground truth information was obtained for each target placed in the UXO test areas at YPG and Eglin AFB. ARL personnel directed and closely monitored all field preparation and target placement activities (see figure 8). To ensure ground truth accuracy, each test target was photographed and the following information was recorded:

- Item number
- Type (e.g., 60-mm mortar, etc.)
- Depth (surface to tail)
- Angle with respect to Boom Road
- Angle of burial (or entry angle)
- Precisely surveyed location coordinates (east, north, elevation)

Figure 9. YPG personnel surveying UXO location.

Complete ground truth information is not available on pre-existing items (e.g., BDU-33 training bombs) that were not removed from TA C-62 at Eglin AFB.

DATA COLLECTIONS

Yuma Proving Ground

Just prior to our BoomSAR data collection in January 1998, the El Niño rainy season brought major rainfall to Yuma. As a result, the soil moisture content climbed to nine percent and a tremendous amount of plant growth appeared. Although the soil conditions were not conducive for detecting underground objects, it gave us the opportunity to assess the impact of soil moisture on radar performance. The vegetation afforded us a unique opportunity to collect valuable clutter data that will be extremely useful in developing and enhancing our clutter reduction.

We conducted our final BoomSAR data collection in June 1998, when soil moisture content was approximately five percent and vegetation was dry and brittle. A total of twelve separate data runs were made from three different paths (Boom Road, Corral Road, and Site 4 Road). Several combinations of radar height and depression angle are represented in these data runs.

Eglin AFB

Due to delays associated with frequency allocation issues, the planned experiment at Eglin AFB will not be executed until after this paper is published.

DATA ANALYSIS AND MODELING

ARL developed an initial structure for data prescreening that utilizes a multi-stage pruning approach in which increasingly sophisticated tests—heavily weighted toward capitalizing on the phenomenological underpinnings—are applied sequentially to the data. After the first test is applied to the data and potential targets are culled, a second test is applied to the winnowed data to further eliminate non-targets, and so on for successive tests. To maintain computational efficiency, the simplest tests are applied first. Amplitude and standard deviation texture features are employed to quickly canvas large image areas. These are followed by more stringent texture tests using spatial templates. Anisotropic scattering characteristic can be used to exploit the fact that some target classes are aspect dependent (e.g., shallow angle impact targets with a large length-to-width ratio, such as rockets), while bushes and mines are more isotropic. Finally, frequency-dependent scattering features are also exploited. All discriminant features are combined with a quadratic polynomial detector (QPD) in a final decision statistic.

The image below, formed from June 1998 YPG data, shows a 200 m x 400 m region of the test area that includes several rows of 155-mm shells, calibration trihedrals, 2.75 in. rockets, missile clones, and test dipoles (see Figure 10).

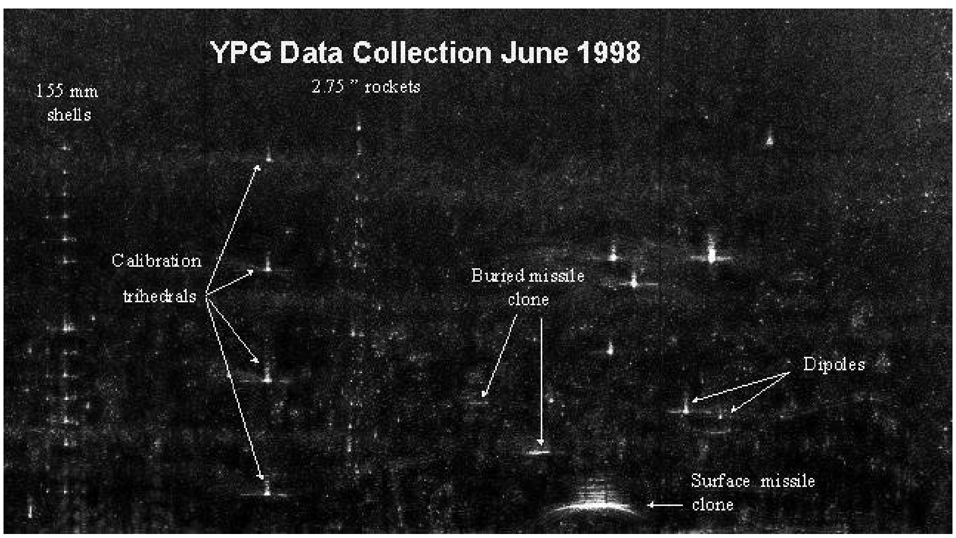


Figure 10. BoomSAR image of (200 m x 400 m) portion of UXO test area at YPG.

With the use of a UWB SAR, three types of diversity could be exploited for detection of targets: (1) frequency diversity, (2) angular diversity, and (3) polarimetric diversity. By far the most salient property of our data is the frequency diversity, due to the wideband nature of our radar. Angular and polarimetric properties, either by themselves or in combination with the frequency information, can also be used to improve detection. The idea of using frequency-dependent scattering features is primarily driven by the need to utilize all available features embedded within the wideband data. This feature offers ease of use coupled with improved performance at the pre-screener, but without substantial changes to the automatic target detection approach.

Our investigators are using a number of graphical analysis tools to reference ground truth files and the underlying bipolar data to analyze the temporal and spectral characteristics of detected objects. The target "chips" below (see figure 11) are generated by an ARL-developed data analysis program that allows the investigator to "point and click" at a target of interest in the overall image and extract a specified area around the target. These particular chips illustrate regions of about 3 m on a side centered on a 155-mm artillery shell in vertical (left) and horizontal (right) polarization. The program extracts the underlying bipolar data for the same region, presenting an equivalent time waveform from the down-range data (upper plot) and the spectrum of that waveform (lower plot).

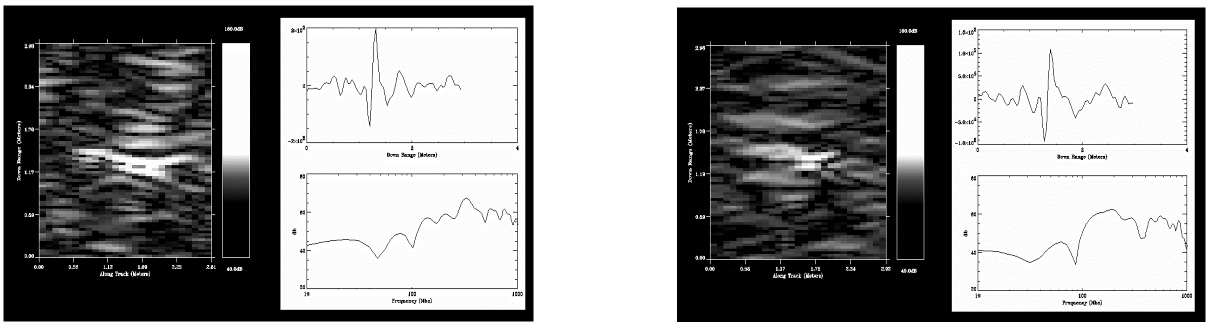


Figure 11. Image chips of 155-mm shell in vertical (left) and horizontal (right) polarization.

High-fidelity electromagnetic models are a key element of this project. Modeling is being done using Finite Difference Time Domain (FDTD), Method of Moments (MoM), Body of Revolution (BoR), and Fast Multi-pole Method (FMM) approaches. These models are being verified by comparing their predictions to experimental data from ground-truthed targets in relatively benign and well-characterized soils. Models hold the promise of predicting performance capabilities with previously untested targets in any soil conditions. They allow examination of a large number of different targets in different orientations and in different soils and clutter.

Models can give insight to the underlying physics that explains observations in experimental data, leading to new target detection algorithms. Investigators can develop algorithms to extract specific features from points of interest and then apply tests to determine how well these features separate targets from clutter or nuisance targets. A detection algorithm analysis framework has been developed to evaluate the performance of the detection features developed by researchers. This analysis framework is based on a multi-dimensional QPD which is trained to choose a best-fit surface to separate the target class from the clutter class. Investigators may examine the performance of individual features with histograms or use scatter plots to view a two-dimensional representation of the QPD surface for multiple feature sets. Another useful format available in the evaluation framework for evaluating the performance of detection algorithms is receiver operating characteristic (ROC) curves which plot probability of detection (P_d) versus probability of false alarm.

In FY98, E/M modeling code was extended to address the configuration of a 155-mm artillery shell (see figure 12), and an initial model was developed.

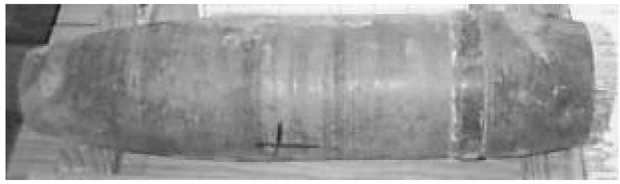


Figure 12. 155-mm artillery shell.

An FDTD model of a 155-mm shell buried in a soil with a dielectric constant of 4 is illustrated in figure 13. The wave enters from the upper right-hand corner, moving down and left at a 45° angle. The reflected wave shows a polarity reversal, while the refracted wave shows a compression in wavelength. Figure 14 is a method-of-moments simulation of relative currents induced on a 155-mm shell model (vertical polarization, YPG 5% moisture soil, depression angle 45^{o}). Results for multiple frequencies can be combined to produce spectral and temporal responses in the far field, as illustrated in figure 15.

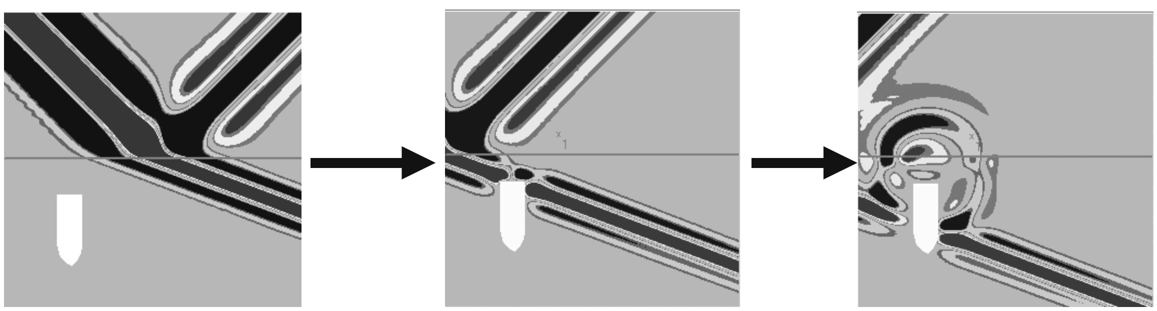


Figure 13. Finite difference time domain model of 155-mm artillery shell.

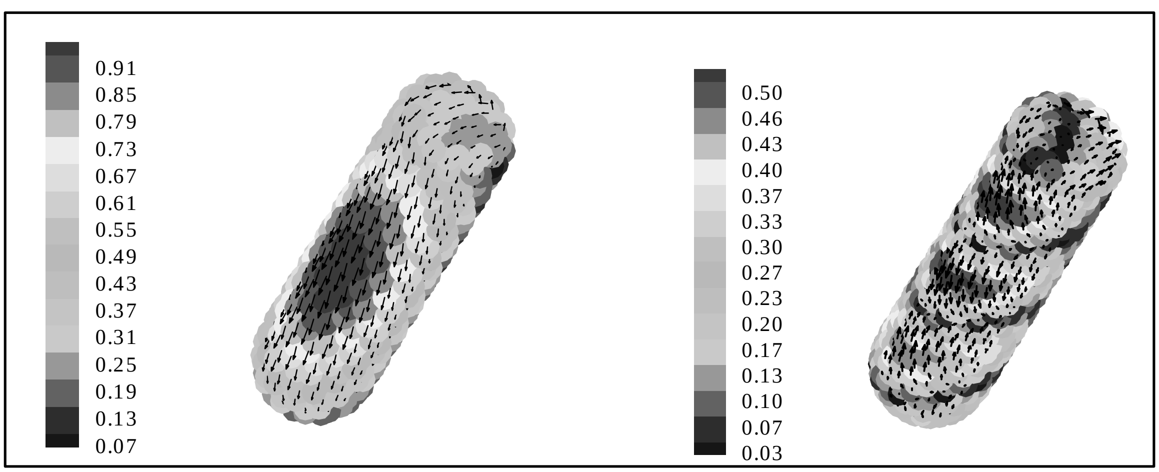
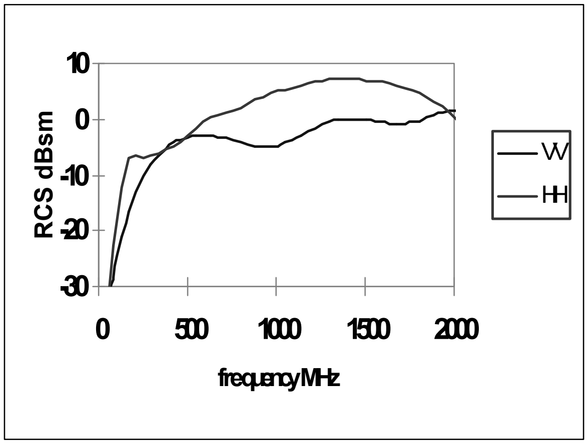


Figure 14. Method-of-moments simulation of a 155-mm artillery shell.



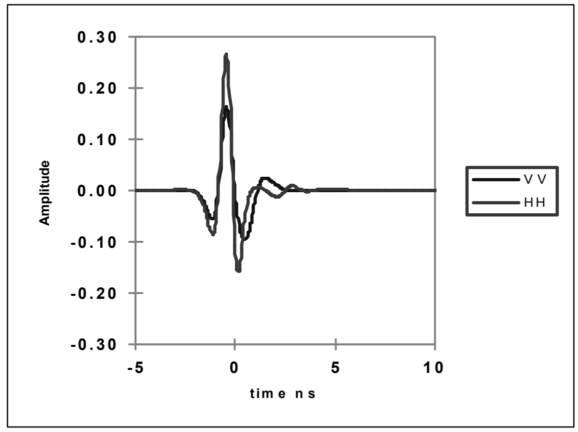


Figure 15. Method-of-moments results for 155-mm model (target broadside to radar, 5% moisture soil at YPG).

CONCLUSION

The ARL BoomSAR is a state-of-the-art instrumentation radar that can provide the high-resolution, high-sensitivity data needed to conduct foliage and ground-penetrating radar investigations. This system complements existing airborne low-frequency SAR systems, because it provides the ability to collect reasonable amounts of data in a very controlled environment with the same geometries as airborne sensors. The unique features of the low-frequency data and the resultant imagery of the data collected with the BoomSAR indicate that there is potential for low-frequency UWB radar to detect targets embedded in foliage and subsurface targets.

A broad set of UWB SAR data on UXO was collected at the extensive UXO test area at YPG. Different combinations of radar path, radar height, and depression angle were used to provide multiple look angles to the targets, which were in various orientations and at various depths. This "real world" data set will (1) support ongoing research efforts aimed at identifying key features and post-processing techniques to incorporate into algorithms to enhance detection and discrimination capability and (2) support the refinement and verification of electromagnetic models of various UXO types. Improved target/clutter discrimination techniques are being developed to reduce false alarm rate, which is the key to making UWB SAR a viable UXO clearance technology.

The UXO test sites at YPG and Eglin AFB are national assets that are available to support the development and demonstration of detection technologies. The careful design and precise installation of these test sites can give technology developers a better understanding of sensor phenomenology, which then could be applied to the development of improved target detection algorithms. For additional information on these two test sites, please contact Clyde DeLuca via e-mail at cdeluca@arl.mil or on 301-394-4163.

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